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Kevin P. Shepherd,
Jack D. Leatherwood,
and Sherman A. Clevenson

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Effect of Low-Frequency Tones and Turbulent-Boundary-Layer Noise on Annoyance

Kevin P. Shepherd
Bionetics Corporation
Hampton, Virginia

Jack D. Leatherwood
and Sherman A. Clevenson
Langley Research Center
Hampton, Virginia

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

SUMMARY

A laboratory study was conducted to examine annoyance to combinations of low-frequency tones and turbulent-boundary-layer noise. A total of 240 sounds, containing tones in the range from 80 to 315 Hz, were rated by 108 test subjects in an anechoic chamber. Seven commonly used noise metrics were calculated for each spectrum. The results indicated that tone penalties (defined as the failure of a noise metric to account for the presence of pure tones) are highly dependent on the choice of noise metric. A-weighted sound pressure level underpredicted annoyance by as much as the equivalent of 5 dB and unweighted sound pressure level overpredicted by as much as the equivalent of 4 dB. Tone penalties were observed to be dependent on the shape of the turbulent-boundary-layer noise spectrum.

INTRODUCTION

Advanced high-speed turboprop aircraft are being developed because of their potential for saving fuel. However, there are concerns about passenger reaction to the interior noise environment which, in comparison to current jet aircraft, is predicted to be both higher in level and of radically different character due to the presence of high-level, low-frequency tones.

Several studies (refs. 1 to 5) have investigated the effects of various combinations of pure tones and broadband noise on annoyance, noisiness, and loudness. In general it has been found that at equal sound pressure level, pure tones combined with bands of noise are judged to be noisier than bands of noise alone. This result implies that the interior noise environment of turboprop aircraft will be less acceptable than interior environments of other aircraft having the same sound pressure level but no tones. However, these previous studies were concerned mainly with tones generated by turbofan engines and, consequently, examined tones at frequencies much higher (above 500 Hz) than those of interest for turboprop aircraft. This study aims to complement previous work by examining annoyance to low-frequency tones superimposed on turbulent-boundary-layer noise. Specific objectives of this study include quantification of passenger annoyance response to tones (at selected frequencies and amplitudes) combined with boundary-layer noise, determination of the effect of boundary-layer noise spectrum level and shape, and quantification of tone penalties in terms of several candidate noise metrics.

SYMBOLS

dB(A)	A-weighted sound pressure level, dB (ref. 6)
dB(D)	D-weighted sound pressure level, dB (ref. 6)
dB(Z)	loudness level (Zwicker), dB (ref. 6)
PNL	perceived noise level, dB (ref. 6)

PNLT	tone-corrected perceived noise level, dB (ref. 6)
PSIL	preferred speech interference level, dB (ref. 6)
SPL	sound pressure level, dB

EXPERIMENTAL METHOD

Test Facility

The testing was conducted in a small anechoic listening room at the Langley Aircraft Noise Reduction Laboratory (fig. 1). This facility has dimensions of 4 by 2.5 by 2.5 m, accommodates two test subjects at a time, and is equipped with a sound reproduction system having a frequency response of 5 Hz to 20 kHz. Further details may be found in reference 7.

Noise Stimuli

Each sound stimulus consisted of a pure tone superimposed on synthesized turbulent-boundary-layer noise. Based on empirical data from a wide range of conventional jet aircraft, two turbulent-boundary-layer spectra were designed to approximate the interior environments of aircraft having either light or heavy applications of noise control materials. Each of these spectra (fig. 2) was presented at 78, 82, and 86 dB(A). The pure-tone frequencies (80, 125, 160, 200, and 315 Hz) were chosen to encompass the blade passage frequencies of both conventional and advanced turboprop aircraft, the latter being associated with the higher frequencies due to the greater number of propeller blades. Each pure tone was presented at eight different sound pressure levels (70, 74, 78, 82, 86, 90, 94, and 98 dB) in combination with each turbulent-boundary-layer condition to yield a total of 240 sounds.

A pink noise generator was used in combination with a spectrum shaper and a pure-tone oscillator to produce the input signals to the anechoic-room sound system. A microphone placed at ear level, midway between the two test-subject positions, was used to set and monitor the sound levels within the room. Each sound was presented for 20 seconds, followed by a brief pause during which the test subjects made their annoyance judgments.

Experimental Design

The experimental design consisted of the factorial combination of four variables: the spectrum and level of turbulent-boundary-layer noise and the frequency and level of superimposed pure tones. The design is summarized in table I. The factorial combination of two boundary-layer spectra presented at three levels and each of five tone frequencies presented at eight levels gives a total of 240 test stimuli. Because of this large number of test stimuli, each subject did not judge every sound. Sixty subjects heard those sounds containing one boundary-layer spectrum and 48 subjects judged those sounds containing the other boundary-layer spectrum. The sequence of presentation of test stimuli was randomized for each group of subjects.

Test Subjects

One hundred and eight subjects were randomly selected from a demographically representative pool of local residents. These paid volunteers, all of whom had normal hearing (within 20 dB of audiometric zero, ANSI 1969), were randomly divided into 54 groups of two subjects each.

Procedure

Upon arrival at the laboratory each subject was given a consent form, an instruction sheet, and a scoring sheet (appendix). After reading the instructions and completing the consent form, the subjects were given an opportunity to ask questions and then escorted to the test facility where they were randomly assigned to their seats. The first 60 noise stimuli were then presented to the subjects. After experiencing each stimulus, the subjects were required to mark their evaluations of that stimulus on the scoring sheet. After a 15-minute rest break the remaining 60 stimuli were presented. A numerical display indicated to the subjects the number of the stimulus that was being presented.

The subjects assessed their annoyance using a 0 to 8 numerical category scale with the ends of the scale labeled "not annoying" and "extremely annoying."

RESULTS

Effect of Tone Level and Frequency

The relationship between mean annoyance and the sound pressure level of the tones for a fixed boundary-layer level and spectrum is shown in figure 3. Results for boundary-layer spectrum A at each spectrum level are given in figures 3(a) to (c) and those for boundary-layer spectrum B are presented in figures 3(d) to (f). These results show that tones at low sound pressure level do not influence the annoyance of the tone/boundary-layer combinations. As the level of the tone is increased, annoyance also increases. This increase is frequency dependent with a clear tendency for the higher frequencies to be the most annoying. It is also apparent that the relative increase in annoyance due to increasing tone level is dependent upon the boundary-layer noise level. For example, the presence of high tone levels within the 86 dB(A) boundary-layer noise spectra produces relatively small increases in annoyance as compared with the effect of the same tones within the 78 dB(A) boundary-layer spectra. All these results are to be expected from consideration of basic loudness theory.

Regression Analysis

The following noise metrics (ref. 6) were calculated for each combination of tone and boundary-layer noise: dB(A), dB(D), perceived noise level (PNL), tone-corrected perceived noise level (PNLT), Zwicker phons (dB(Z)), preferred speech interference level (PSIL), and sound pressure level (SPL). The results of linear regression analysis of mean annoyance and each of these metrics are presented in table II. The slopes of the regression lines are consistently greater for those sounds containing boundary-layer spectrum B. At equal A-weighted sound pressure

levels, the boundary-layer noise spectrum B has greater low-frequency content than spectrum A (fig. 2). This results in a smaller range of sound levels for those stimuli containing boundary-layer spectrum B relative to those containing boundary-layer spectrum A. Since these two sets of stimuli were assessed by different groups of subjects it is probable that the smaller range of sound levels for the stimuli containing boundary-layer spectrum B is responsible for the larger regression coefficients (slope) in table II. For the remaining analyses the two sets of data are therefore examined independently.

Table II indicates that all the noise metrics perform approximately equally well with the exception of speech interference level. The explanation for the poor performance of PSIL is simply the failure of this measure to account for the low-frequency tones used in this experiment. (PSIL does not consider frequencies below the 500-Hz octave band.)

Tone Penalties

A more detailed examination of the effect of the tones was conducted with the aid of regression analysis using dummy variables. (See, for example, ref. 8.) The experimental design can be viewed, in part, as consisting of certain tone/boundary-layer combinations presented at three sound pressure levels, 4 dB apart. For example, a tone at a sound pressure level of 82 dB combined with boundary-layer noise at 78 dB(A) has precisely the same spectral shape as an 86-dB tone with boundary-layer noise at 82 dB(A) or a 90-dB tone with boundary-layer noise at 86 dB(A). A regression line relating mean annoyance to the sound pressure level of this tone/boundary-layer combination enables "tone penalties" to be calculated. This procedure is illustrated in figure 4. A tone penalty is defined as the deviation of the regression line of a tone/boundary-layer combination from the regression line of the boundary layer with no added tones. (Some sounds used in this study contain tones which are completely masked by the boundary-layer noise and were thus considered to be no-tone conditions.) A positive tone penalty results from a tone/boundary-layer combination being judged more annoying than the boundary layer with no tone when they are presented at the same sound level. Multiple regression analysis using dummy variables is a convenient method for determining these tone penalties.

Figures 5 and 6 display the calculated tone penalties in terms of various metrics as a function of the ratio of the tone sound pressure level to the boundary-layer sound pressure level (measured in the one-third-octave band containing the tone). The standard error associated with any particular tone penalty was calculated to be typically 0.8 dB, and thus it is clear that some of the tone penalties are significantly different from zero. For example in figure 5, dB(A) underpredicts annoyance by as much as 5 dB, PSIL underpredicts annoyance by as much as 11 dB, and SPL overpredicts annoyance by as much as 4 dB. There is apparently no simple relationship between tone penalties and the ratio of tone sound pressure level to boundary-layer noise level (tone/noise ratio). The lowest tone levels result in zero tone penalties since they are of insufficient magnitude to affect either annoyance or the sound level of the tone/boundary-layer combination. As the tone/noise ratio is increased, at some point the tone will influence either the annoyance, the sound level of the tone/boundary-layer combination, or both. If annoyance increases without an accompanying increase in sound level, a positive tone penalty results. If the increase in annoyance is perfectly matched by an increase in sound level, no tone penalty results. It is clear, therefore, that observed tone penalties will always vary as a function of the choice of noise metric. The perfect noise metric would, of course, take full account of the tones and yield no tone penalties.

Table III summarizes the tone penalties presented in figures 5 and 6. The mean, standard deviation, and range of tone penalties are given for each metric. An extreme example is provided by PSIL, which takes no account of the tone frequencies used in this study. In other words, the sound pressure level of the tones may be raised without limit, and the value of PSIL will remain the same. Large positive tone penalties are therefore expected and observed. Of the other metrics, no single one is outstanding.

Confining attention to the simple weighted sound level scales, it may be noted that as emphasis of the low frequencies is increased (PSIL → dB(A) → dB(D) → SPL), there is a strong tendency for the mean value of the tone penalties to decrease. This trend may be readily observed in figures 5 and 6, particularly for the high tone/noise ratios. Consider, for example, the 125-Hz tone at a tone/noise ratio of 22 dB shown in figure 5. The tone penalty associated with this stimulus clearly decreases as the low-frequency emphasis of the metric is increased.

Examination of the statistics for PNL and PNLT in table III indicates that the tone corrections embodied in the calculation procedure for PNLT are ineffective. This result agrees with the conclusion drawn from figures 5 and 6 that a linear relationship between tone penalties and tone/noise ratio does not exist.

Because of the shape and level of boundary-layer spectrum B (fig. 2), the maximum values of the ratio of tone to boundary-layer noise are less than those of the sounds containing boundary-layer spectrum A. This difference might be expected to result in the mean of the tone penalties being closer to zero for those sounds containing boundary-layer spectrum B. Table III reveals no such trend. Similarly there is no indication that the range of tone penalties is systematically less for those sounds containing boundary-layer spectrum B. Since the tone penalties are not clearly related to tone/noise ratio (fig. 6), this latter finding is not surprising.

Examination of the tone penalties (table III) shows that, with the exceptions of SPL and PSIL, if a metric performs well (low standard deviation and range) for the sounds containing boundary-layer spectrum A, it performs relatively poorly for those sounds containing boundary-layer spectrum B, and vice versa. There is also a strong tendency for the mean tone penalties for the sounds containing boundary-layer spectrum A to be greater than those for the sounds containing boundary-layer spectrum B. In other words, there is an interaction between tone penalties and the shape of the boundary-layer spectrum. The explanation for this result is far from clear but is probably related to complex masking of tones by boundary-layer noise and vice versa.

CONCLUSIONS

Two hundred and forty sounds, consisting of various combinations of low-frequency pure tones superimposed on turbulent-boundary-layer noise, were rated by 108 test subjects using a numerical annoyance scale. The tests were performed in an anechoic chamber. The main conclusions were as follows:

1. When tones are presented at a sound pressure level of sufficient magnitude to influence the annoyance of the tone/boundary-layer noise combination, mean annoyance generally increases with increasing tone frequency over the range considered (80 to 315 Hz).

2. Tone penalties (defined as the failure of a noise metric to account for the presence of pure tones) are highly dependent on the choice of noise metric. For the

range of conditions examined, speech interference level underpredicts annoyance by as much as the equivalent of 11 dB, A-weighted sound pressure level underpredicts by as much as the equivalent of 5 dB, and unweighted sound pressure level overpredicts by as much as the equivalent of 4 dB.

3. Tone corrections employed in the perceived noise level calculation procedure are ineffective for the range of frequencies examined.

4. Tone penalties were observed to be dependent on the shape of the turbulent-boundary-layer noise spectrum.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
July 14, 1983

APPENDIX

CONSENT FORM, INSTRUCTIONS, AND SCORING SHEET

VOLUNTARY CONSENT FORM FOR SUBJECTS

FOR HUMAN RESPONSE TO AIRCRAFT NOISE AND VIBRATION

I understand the purpose of the research and the technique to be used, including my participation in the research, as explained to me by the Principal Investigator (or qualified designee).

I do voluntarily consent to participate as a subject in the human response to aircraft noise experiment to be conducted at NASA Langley Research Center on ____________________________.
date

I understand that I may at any time withdraw from the experiment and that I am under no obligation to give reasons for withdrawal or to attend again for experimentation.

I undertake to obey the regulations of the laboratory and instruction of the Principal Investigator regarding safety, subject only to my right to withdraw declared above.

I affirm that, to my knowledge, my state of health has not changed since the time at which I completed and signed the medical report form required for my participation as a test subject.

____
PRINT NAME

____
SIGNATURE

NASA Langley (November 1979) ANRD-NEB N-115

APPENDIX

INSTRUCTIONS

You have volunteered to participate in a research program to study the annoyance due to various noises (or sounds). Specifically, we wish to identify particular noises which you find annoying. To accomplish this you will be asked to listen to a series of noises and to mark your evaluations of each noise. You will be asked to make two evaluations of each noise that you hear. First, you will mark in the appropriate blank (see below) your overall evaluation of whether the noise was "annoying" to you or "not annoying" to you. Second, you will place a checkmark along the scale shown below to show how annoyed you were by the noise. Note that zero on the scale means that you were "not annoyed" and eight on the scale means that you were "extremely annoyed." Your evaluation sheets may look something like the following:

	Not Annoyed	Annoyed	Not Annoyed								Extremely Annoyed
1.	______	______	0	1	2	3	4	5	6	7	8
2.	______	______	0	1	2	3	4	5	6	7	8
3.	______	______	0	1	2	3	4	5	6	7	8
4.	______	______	0	1	2	3	4	5	6	7	8

On top of the speaker in front of your seats in the test room you will see a box which will display a number. This number will indicate the number of each noise that you listen to. Immediately after a noise stops, please mark your evaluations in the blank space and scale next to the number that was displayed during the playing of the noise. The numbers will increase in sequence and are provided to help you keep track of which noise you will be evaluating.

Please try to evaluate each noise without looking at the evaluations of previous noises. Also, do not be concerned about whether your evaluations agree with the other person in the room with you. We want to know how you feel about the noises.

<u>Remember</u>

- Listen carefully to each noise.
- Look at the number display box to check the number of the noise you are evaluating.
- Mark your evaluation on the appropriate blank.

<u>Are there any questions?</u>

APPENDIX

SESSION ________ SUBJECT ________

DATE ________

NOT ANNOYING	ANNOYING		Not Annoying								Extremely Annoying
______	______	1.	0	1	2	3	4	5	6	7	8
______	______	2.	0	1	2	3	4	5	6	7	8
______	______	3.	0	1	2	3	4	5	6	7	8
______	______	4.	0	1	2	3	4	5	6	7	8
______	______	5.	0	1	2	3	4	5	6	7	8
______	______	6.	0	1	2	3	4	5	6	7	8
______	______	7.	0	1	2	3	4	5	6	7	8
______	______	8.	0	1	2	3	4	5	6	7	8
______	______	9.	0	1	2	3	4	5	6	7	8
______	______	10.	0	1	2	3	4	5	6	7	8

NASA Langley (July 1981) ANRD-NEB

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TABLE I.- EXPERIMENTAL DESIGN

Turbulent-boundary-layer noise:
  2 spectra (fig. 2)
  3 levels (78, 82, and 86 dB(A))

Pure tones:
  5 frequencies (80, 125, 160, 200, and 315 Hz)
  8 levels (70, 74, 78, 82, 86, 90, 94, and 98 dB)

TABLE II.- REGRESSION OF MEAN ANNOYANCE ON VARIOUS NOISE METRICS

Metric	Boundary-layer spectrum A			Boundary-layer spectrum B		
	Slope	Intercept	Correlation coefficient	Slope	Intercept	Correlation coefficient
dB(A)	0.301	-20.82	0.920	0.329	-22.88	0.964
dB(D)	.284	-20.97	.958	.317	-23.88	.953
PNL	.296	-24.08	.961	.311	-25.08	.947
PSIL	.213	-12.14	.604	.277	-15.72	.749
dB(Z)	.375	-32.98	.894	.410	-35.18	.951
PNLT	.281	-23.39	.961	.298	-25.68	.952
SPL	.246	-17.92	.915	.324	-25.69	.924

TABLE III.- SUMMARY STATISTICS OF TONE PENALTIES

Metric	Boundary-layer spectrum A			Boundary-layer spectrum B		
	Mean	Standard deviation	Range	Mean	Standard deviation	Range
dB(A)	1.73	1.23	6.06	0.02	0.61	2.89
dB(D)	.79	.71	3.15	-.56	.94	3.89
PNL	.61	.67	2.66	-.76	1.03	4.18
PSIL	3.34	3.29	12.21	1.39	2.21	9.38
dB(Z)	1.50	1.23	5.00	.25	.65	2.84
PNLT	.61	.72	2.78	-.67	.96	4.06
SPL	-.45	1.54	5.30	-.48	1.23	6.08

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Figure 1.- Anechoic listening room in Langley Aircraft Noise Reduction Laboratory.

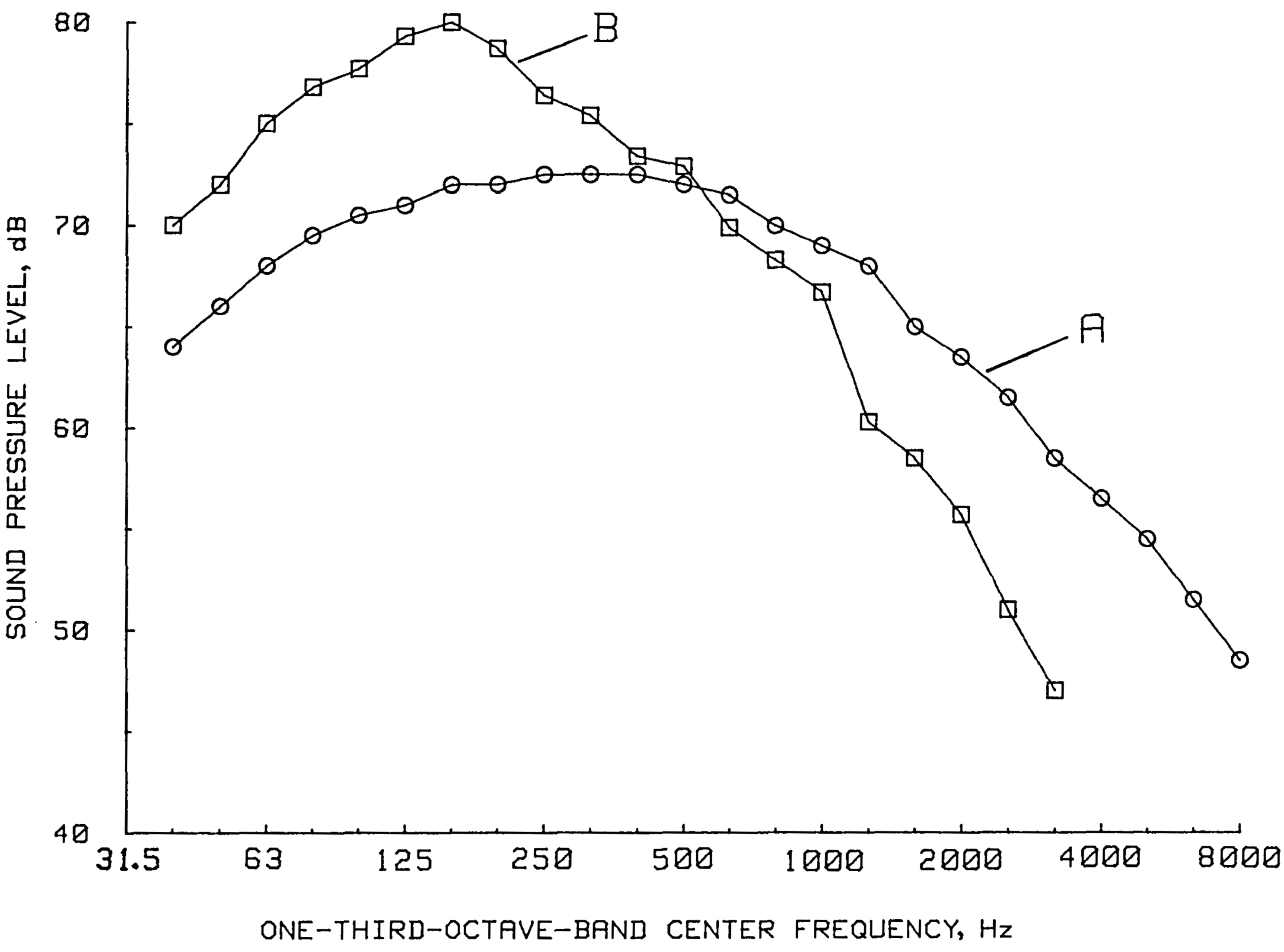


Figure 2.- Turbulent-boundary-layer noise spectra (78 dB(A)).

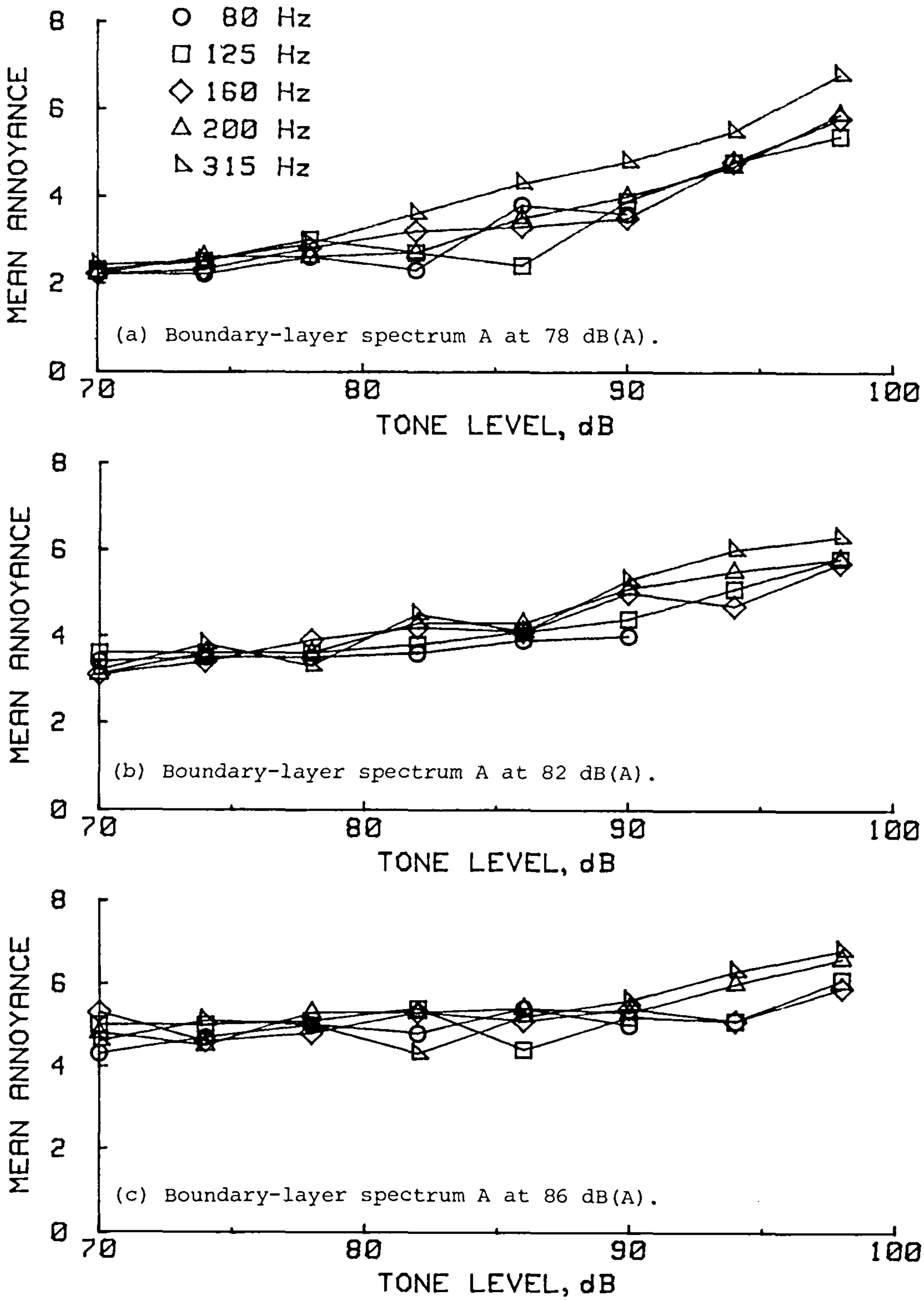
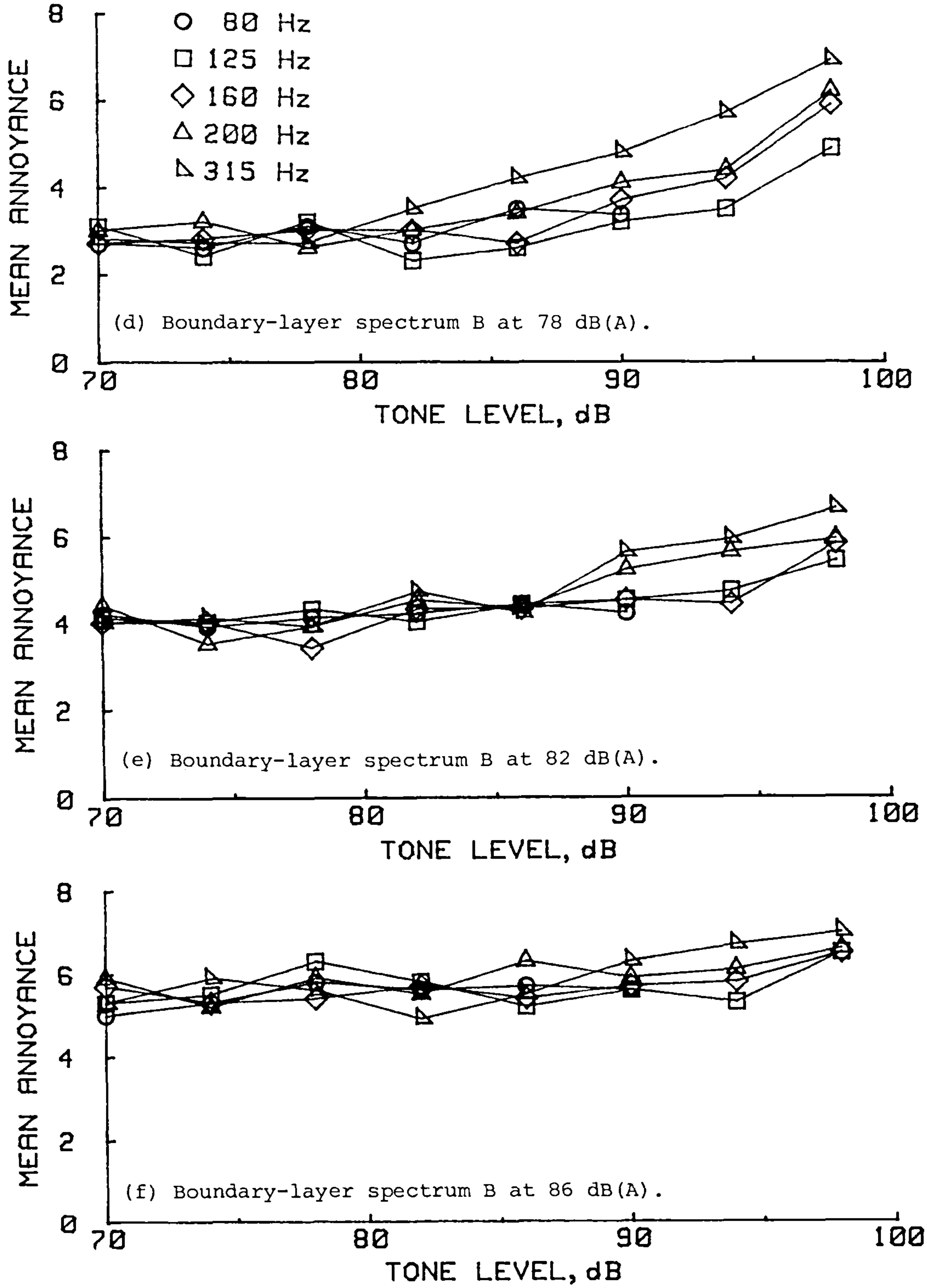


Figure 3.- Mean annoyance as a function of tone level.



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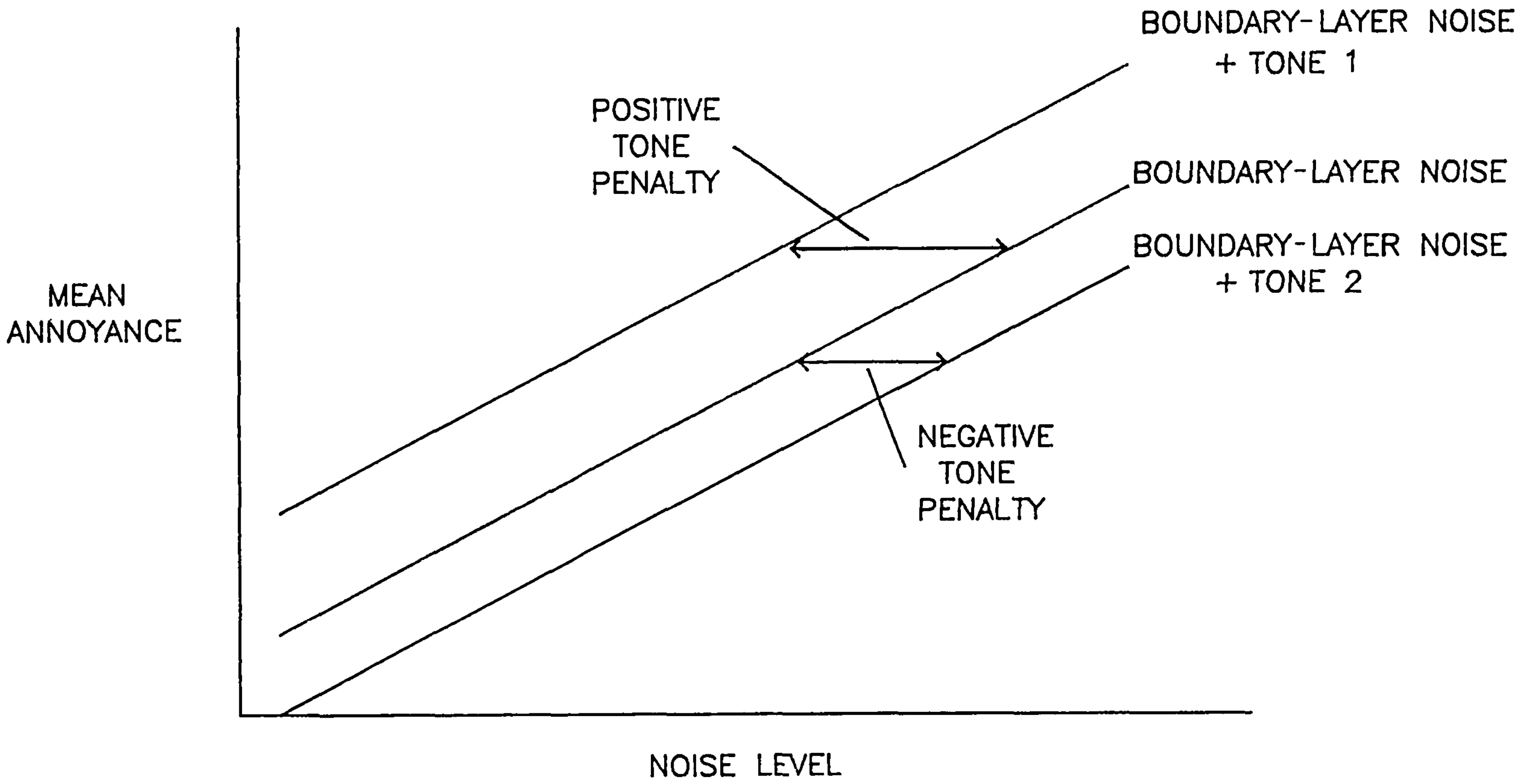


Figure 4.- Derivation of tone penalties.

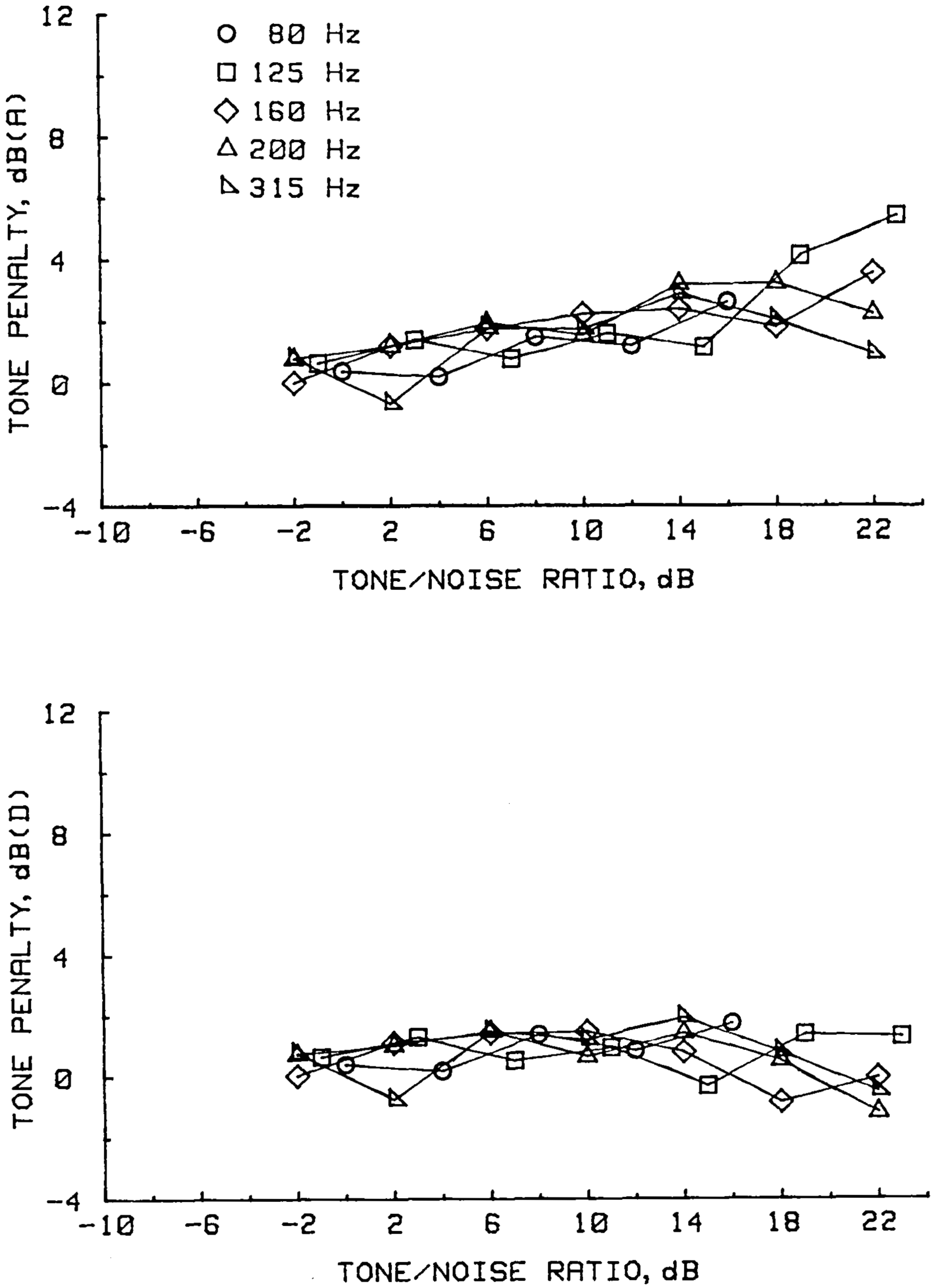
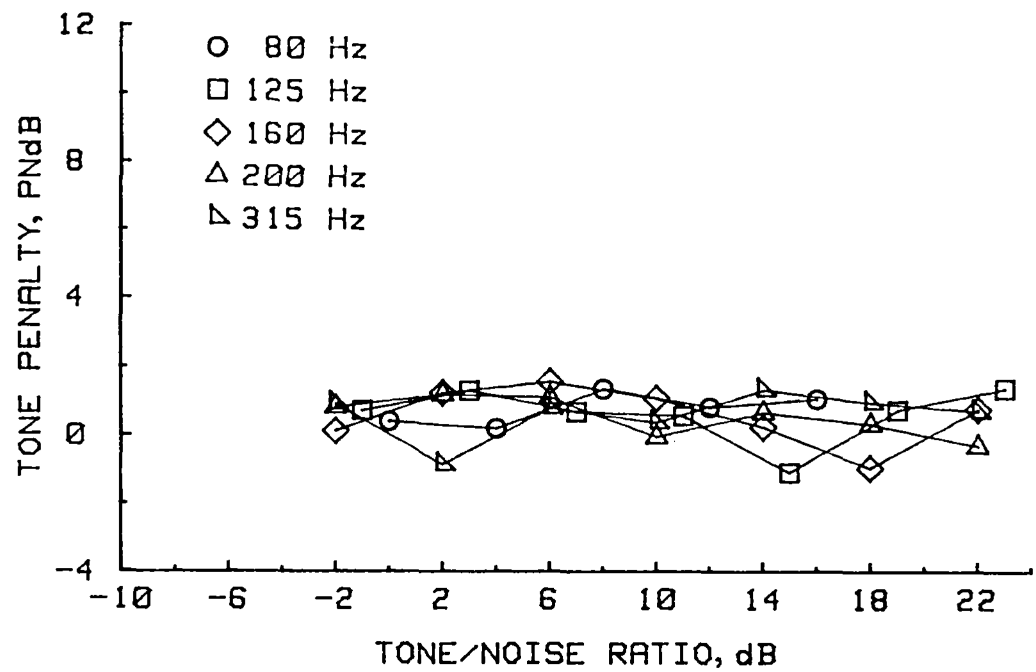
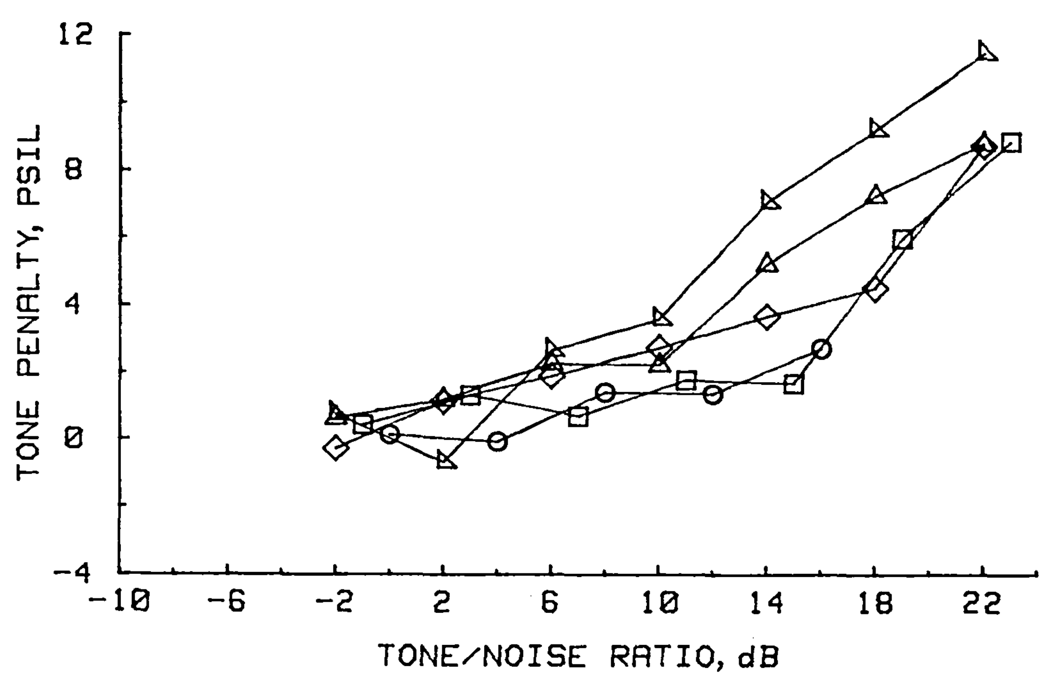


Figure 5.- Tone penalties for several noise metrics and boundary-layer spectrum A.





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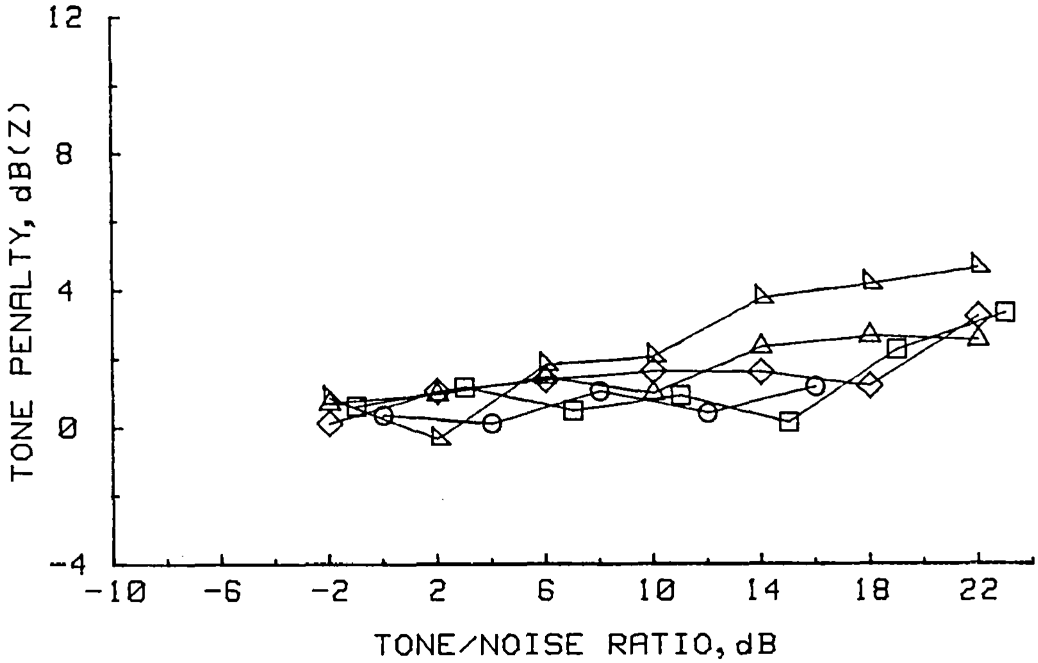

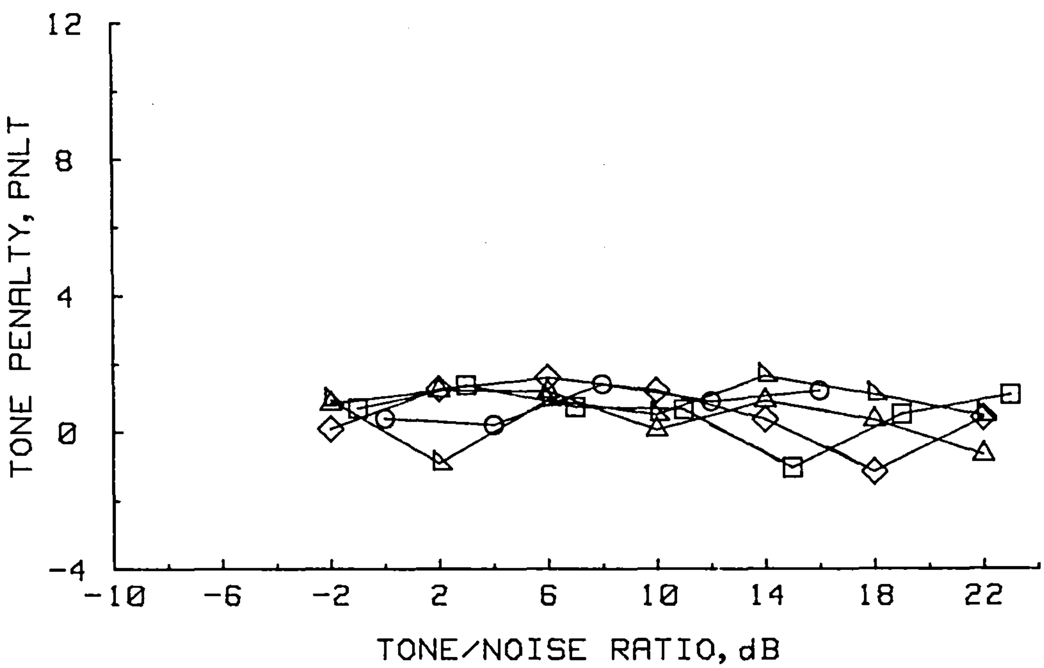

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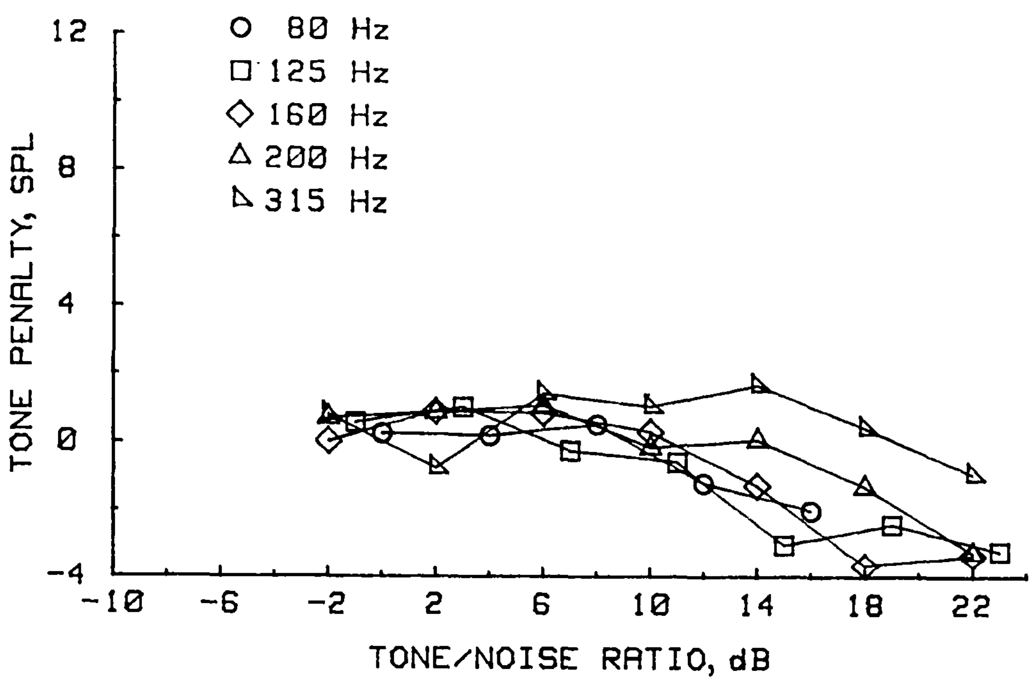

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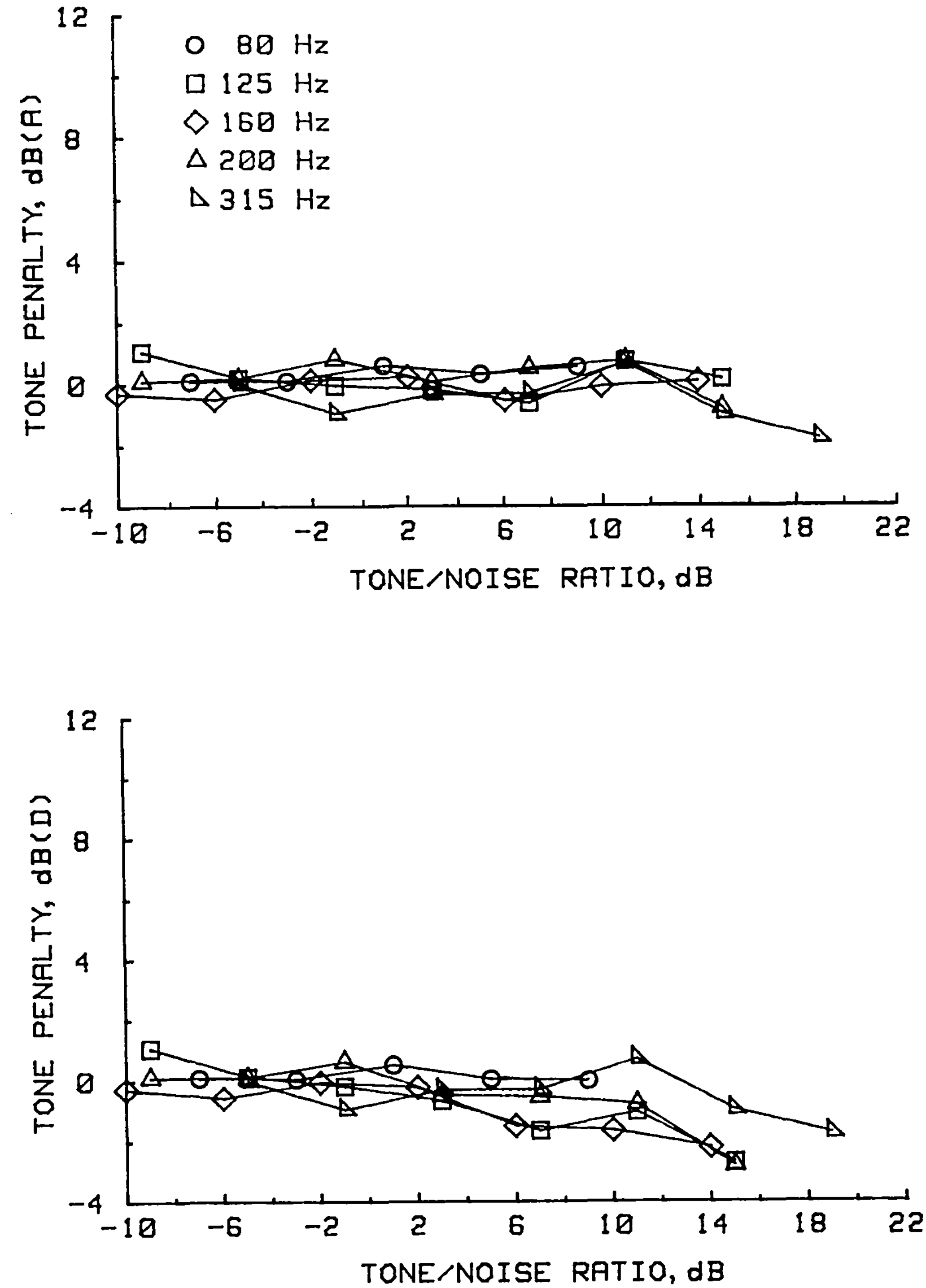
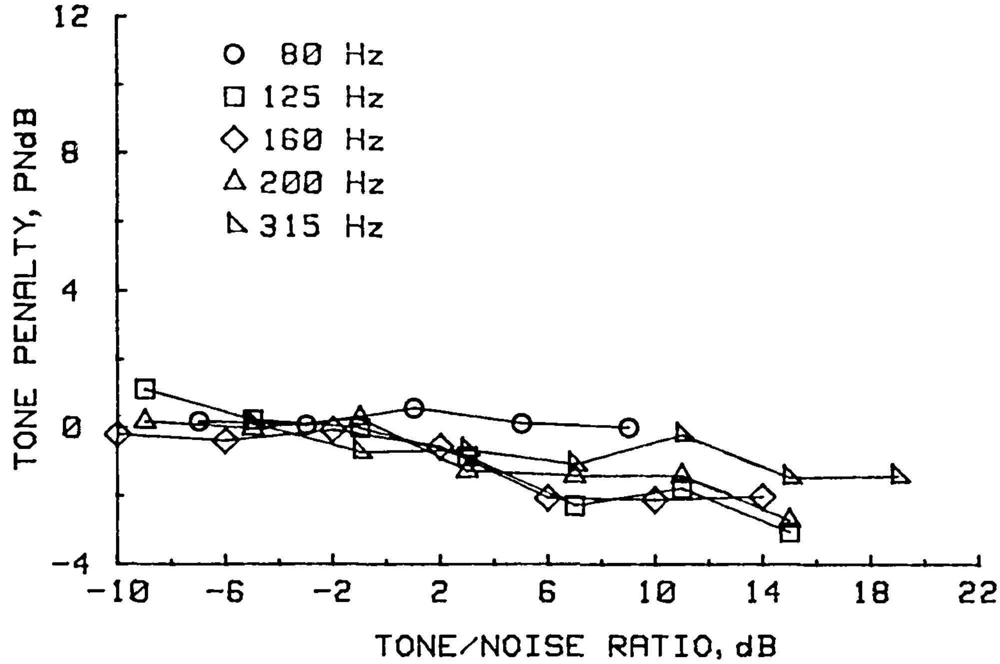
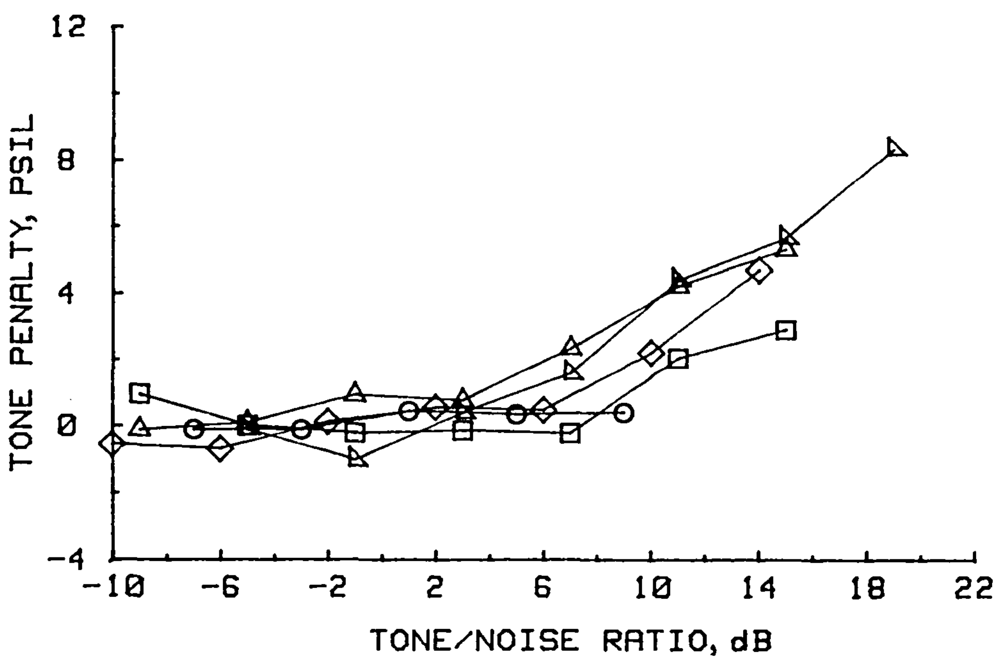


Figure 6.- Tone penalties for several noise metrics and boundary-layer spectrum B.





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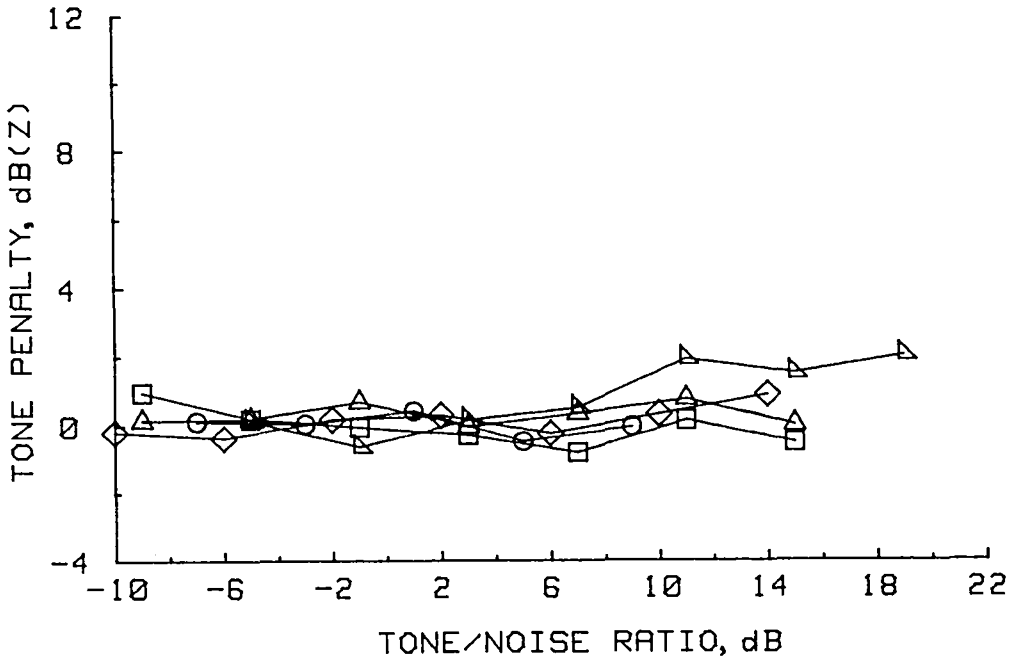

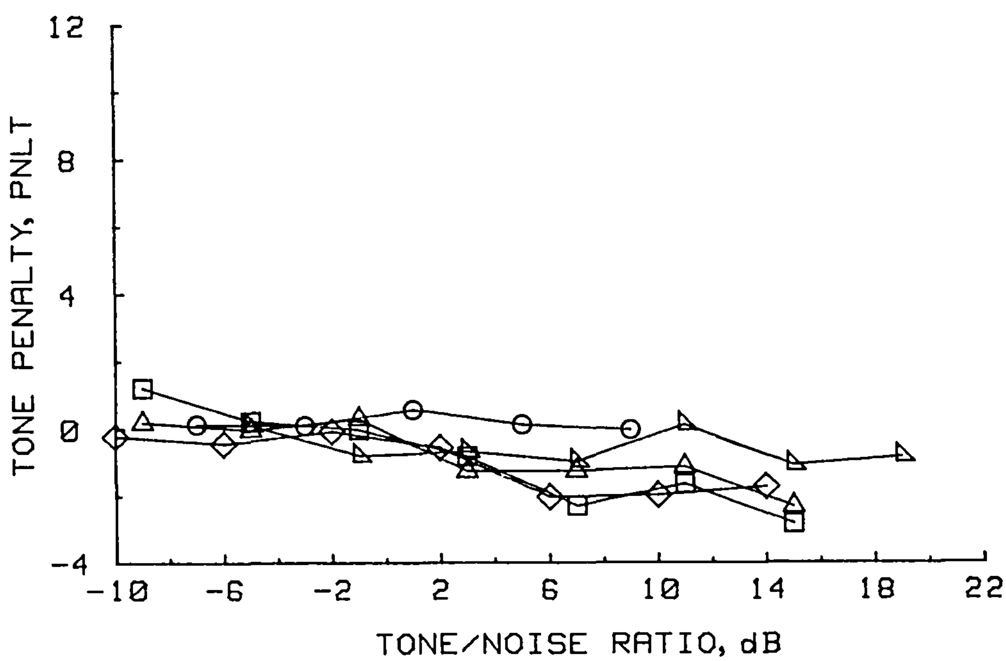

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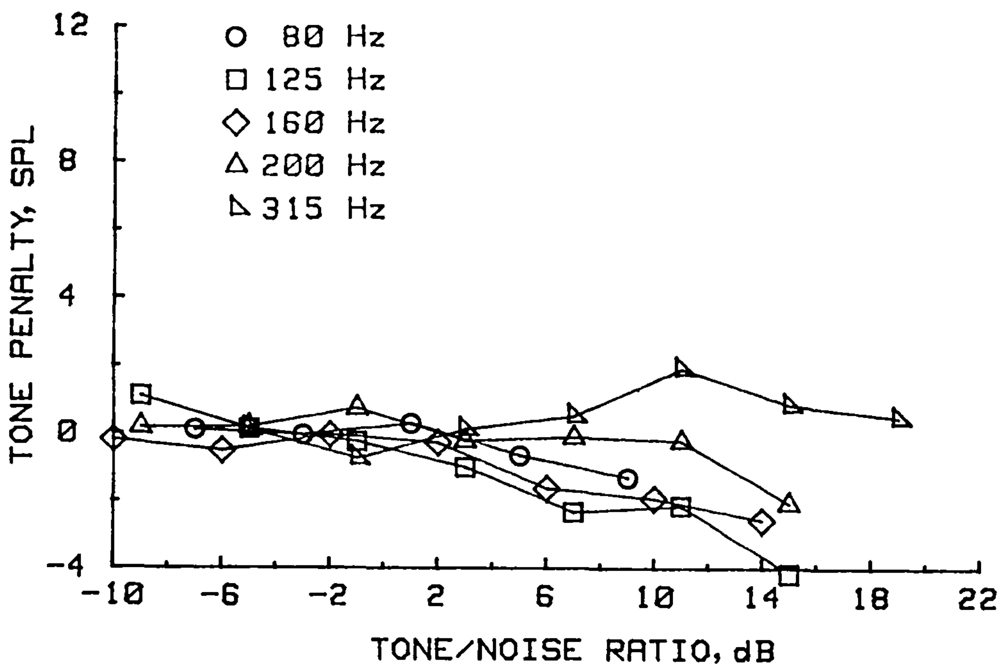

Figure 6.- Concluded.

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15. Supplementary Notes

Kevin P. Shepherd: Bionetics Corporation, Hampton, Virginia.
Jack D. Leatherwood and Sherman A. Clevenson: Langley Research Center, Hampton, Virginia.

16. Abstract

A laboratory study was conducted to examine annoyance to combinations of low-frequency tones and turbulent-boundary-layer noise. A total of 240 sounds, containing tones in the range from 80 to 315 Hz, were rated by 108 test subjects in an anechoic chamber. The results indicated that tone penalties (defined as the failure of a noise metric to account for the presence of pure tones) are highly dependent on the choice of noise metric. A-weighted sound pressure level underpredicted annoyance by as much as the equivalent of 5 dB and unweighted sound pressure level overpredicted by as much as the equivalent of 4 dB. Tone penalties were observed to be dependent on the shape of the turbulent boundary-layer noise spectrum.

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